Behaviour of Asymmetrical Friction Connections using different shim materials

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ABSTRACT: Asymmetrical Friction Connections (AFC) have been successfully applied in New Zealand. Testing on small components, and beam column joint subassemblies have demonstrated stable, efficient hysteretic behaviour with almost no damage. This paper reports quasi-static testing of full scale AFC specimens using different shim materials: mild steel, aluminium, brass, bisalloy grades 80, 400 and 500. The assembling process and hysteretic behaviour of the connections are described. Effects of different shim materials on the hysteresis loop stability and on the magnitude of the friction force are also discussed. Results show stable hysteretic behaviour and minimum degradation effects using shim materials with high Brinell hardness values ranging from 300BH to 500BH.

1 INTRODUCTION

Asymmetrical Friction Connections (AFC) were developed by Clifton (2005). Initial development used brass shims following the energy dissipation mechanism proposed by Grigorian and Popov (1994) for slotted bolted connections. Subsequent studies carried out by Mackinven (2006) extended the application of the SHJ concept to mild steel and aluminium shims. Recent studies carried out by Khoo et. al. (2011) introduced the use of bisalloy grades 80 and 400 shims. Although these studies have characterized the hysteresis behaviour using different shim materials, they only validated the concept on subassemblies where displacement demand was less than 50mm. This limitation requires the experimental validation of this concept for superior displacement demands. This paper aims to answer:

i) What is a reliable construction methodology to assemble Asymmetrical Friction Connections?

ii) What is the effect of different shim materials on hysteresis loop stability and friction force?

iii) What is the effect of increasing sliding length on hysteresis loop shape?

2 ASSYMETRICAL FRICTION CONNECTIONS (AFC)

Asymmetrical Friction Connections (AFC) can be described as an arrangement of five plates, three steel plates and two thinner plates termed shims assembled using high strength bolts. Figure 1 show the basic components and assembly of an AFC specimen. Eight AFC specimens divided in two groups were tested, the first group comprised specimens with 80mm slot length using steel and brass shims, and the second group comprised six AFC specimens with 220mm slot length using aluminium, brass, steel and bisalloy grade 80, 400 and 500 shims. Both groups of specimens were assembled using Grade 300 steel plates with 16mm thickness and M16 Grade 8.8 galvanized bolts with 90 mm length. Shim material properties are presented in Table 1.
Figure 1. Components and assembling of Asymmetrical Friction Connections (AFC)

Table 1. Summary of materials used for shim plates

<table>
<thead>
<tr>
<th>Material</th>
<th>Specification</th>
<th>Brinell Hardness (BH)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>5005GP Series</td>
<td>75</td>
<td>3.0</td>
</tr>
<tr>
<td>Brass</td>
<td>UNS C26000 ~ 1/2 Hard Temper</td>
<td>82</td>
<td>3.0</td>
</tr>
<tr>
<td>Steel</td>
<td>Cold Rolled Mild Steel</td>
<td>130</td>
<td>3.0</td>
</tr>
<tr>
<td>Bisalloy 80</td>
<td>Bisplate 80</td>
<td>255</td>
<td>3.0</td>
</tr>
<tr>
<td>Bisalloy 400</td>
<td>Bisplate 400</td>
<td>400</td>
<td>6.0</td>
</tr>
<tr>
<td>Bisalloy 500</td>
<td>Bisplate 500</td>
<td>500</td>
<td>6.0</td>
</tr>
</tbody>
</table>

3 EXPERIMENTAL METHODS

Testing was carried out on a DARTEC universal machine using a vertical setup as show in Figure 2. The AFC specimens were connected to two slip critical connections respectively attached to the frame cross head and to the hydraulic ram. These slip critical connections were placed eccentrically in order to allow the asymmetry of the AFC specimens. The setup was instrumented with a load cell connected in series with the moving slip critical connection and the hydraulic ram, and with a potentiometer placed across the stroke of AFC specimen. The maximum test sliding length was defined as ± 95 mm.
AFC specimens were subjected to 20 sinusoidal cycles divided into six displacement regimes with variable amplitude as shown in Figure 3. Amplitudes were chosen based on increasing the sliding length from 6.25% to 100% of the specimen slot length. The maximum velocity of the sinusoidal cycles was 10mm/s. For this velocity and the different amplitudes, frequencies ranged between 0.017 - 0.27 Hz for specimens with 220mm slot and 0.064 - 1.0 Hz for specimens with 80mm slot.

![Figure 3. Imposed displacement regime](image)

According the New Zealand Steel Construction Standard (NZS 3404, 2009) friction type connections shall be assembled guaranteeing that the minimum tension force per bolt is the proof load. In addition, only the part turn method and the direct tension indication device method are permitted for bolt tensioning purposes. Although, these methods are generally accepted as typical construction practices in New Zealand, they cannot be directly applied to AFC assembly because i) these methods were not developed considering the friction component produced by Belleville washers, and ii) they cannot predict accurately the tension force level on the bolts. Thus, these methods can lead to high variability on the minimum bolt tension force that consequently affects the predicted sliding force. This issue can be seen in the Equation 1 (MacRae et.al. (2010)) where, $F_s$ is the sliding force, $n$ is the number of bolts, $\mu$ is the friction coefficient, $\eta$ is the number of shear planes, and $N_{tf}$ is the proof load per bolt.

$$F_s = n \times \mu \times \eta \times N_{tf}$$

Alternatively, the torque control method can be used for assembling Asymmetrical Friction Connections. This method is based on tighten the bolts to certain amount of torque defined from an experimentally developed torque – bolt tension relationships. This method is not generally accepted for structural applications according the New Zealand Steel Construction Standard (NZS 3404, 2009). However, it was considered in this research as a first approach to minimize the limitations, and provide a constant bolt tension.

4 RESULTS AND ANALYSIS

4.1 Torque control method for Asymmetrical Friction Connections.

Aiming to assemble Asymmetrical Friction Connections (AFC) using an objective and controllable construction methodology that considers the proof load requirements and the effect of Belleville washers the torque control method was experimentally implemented. Figure 4 shows the data recorded from the axial testing of three bolts and the induced bolt elongation, nut rotation and torque data recorded from assembling five AFC specimens. Results show that the proof load can be reached when the bolt shank elongation is about 0.175mm (Figure 4a). To induce similar bolt shank elongation a torque of 320 - 460kN-m should be applied as shown in Figure 4b. According these results a torque value of 390kN-m was recommended for assembling AFC specimens. If the part turn method is used, a nut rotation of 80-115 degrees should be expected (Figure 4c). Thus, an average nut rotation value of
97.5 degrees or close to 1/4 nut rotation was recommended to carry out post assembling controls of AFC specimens. This value disagrees with the 1/2 nut rotation value recommended by the New Zealand Steel Construction Standard (NZS 3404, 2009) where a bolt failure due to excessive induced tension is expected (Figure 4c).

![Figure 4. Torque-control method relationships for AFC specimens using Belleville washers](image)

4.2 Sliding length effect on the hysteresis loop shape of AFC specimens

Previous research works (Clifton (2005), Mackinven (2006), MacRae et.al. (2010), and Khoo et.al. (2011)) reported bilinear hysteresis loop shapes. In contrast, this research shows that the hysteresis loop shape of AFC specimens depends on the sliding length as shown in Figure 5. A bilinear shape was found for sliding lengths less than 50mm and was more accentuated when decreasing the sliding length. However, for sliding lengths of 50-220mm the hysteresis loop shape changes gradually from bilinear to almost square. This change can be attributed to the sliding length required by the connection to move from the first sliding state to the fully activation of the two sliding interfaces (segment a-b in Figure 5a). This sliding distance is termed activation length and was found to range from 4mm to 6mm. In the case of connections tested over small sliding lengths the activation length can be considered representative when compared with the hysteresis loop amplitude, thus generating bilinear loop shapes. As the sliding length increases the participation of the activation length over the hysteresis loop amplitude reduces gradually, so that the hysteresis loop can be considered as almost square for sliding lengths bigger than 96mm.

![Figure 5. Hysteresis loop of AFC specimen when testing on different sliding lengths](image)
4.3 Shim material effects on the hysteresis loop stability of AFC specimens

The hysteresis loop stability of AFC specimens can be described considering three groups of shim materials defined according to the Brinell hardness value (BH). The first group correspond to shim materials with low hardness values ranging from 70BH to 100BH, in this group 5005 GP series aluminium and UNS C2600 brass – ½ Hard Temper were tested. Hysteresis loops in this category can be described as moderately stable with slight differences on the dynamic friction force levels when comparing the behaviour of the specimen on small and long sliding lengths as it can be seen in Figures 7a and 7b. The moderate hysteresis loop stability in this group can be attributed to the small amount of wear particles produced during the sliding mechanism. These particles generate minor surface degradation given that they adhere to the sliding surfaces; thus exhibiting an adhesive wear mechanism as defined by Grigorian and Popov (1994). The second group comprises shim materials with medium hardness values ranging from 100BH to 300BH; shim materials such as Grade 300 steel and bisalloy Grade 80 were tested. Hysteresis loops in this category can be considered as unstable; their instability was found to increase with the sliding length. This characteristic is more accentuated for steel shims rather than for bisalloy 80 shims as it can be seen Figures 7c and 7d. The instability of the hysteresis loop in this group can be attributed to the large amount of work hardened wear particles produced during the sliding mechanism. These particles abrade the sliding surfaces in an irregular pattern thus exhibiting a wear abrasive mechanism as defined by Grigorian and Popov (1994) and Khoo et.al. (2011). And the last group correspond to shim materials with high hardness levels ranging from 300BH to 500 BH, shim materials such as bisalloy400 and bisalloy500 shims were tested. Hysteresis loops in this category can be considered as stable, only minor differences on the dynamic force levels were found when comparing the behaviour of specimens on small and long sliding lengths as shown in Figures 7e and 7f. The reason for the stable behaviour in this category is associated to the minimum volume of wear particles produced during the sliding mechanism. These particles either are transferred back to the sliding surfaces or fall out as loose debris producing minimal surface degradation thus exhibiting a slight adhesive wear as defined by Grigorian and Popov (1994).

![Hysteresis loop shape for different shim materials](image)

**Figure 7.** Hysteresis loop shape for different shim materials
4.3.1 Shim material effects on the static and dynamic friction force levels

The static friction force is considered as the maximum force that can be applied on the connection before any sliding occurs. The effect of different shim materials on this value is presented in Figure 8. Results show that higher static friction force levels were exhibited by specimens using aluminium, brass, bisalloy 400 and bisalloy 500 shims, which are respectively characterized with low and high Brinell hardness values and lower levels were exhibited by specimens using steel and bisalloy 80 shims.

![Force-Displacement curve for different shim materials](image)

**Figure 8.** Force-Displacement curve from rest condition to first sliding for different shim materials

The dynamic friction force can be interpreted as the maximum force level developed by the connection when sliding. The magnitude of this force was calculated as the average value across the hysteresis loop plateau, values for different shim materials are presented in Table 3. Results show that higher dynamic friction force were found for steel and bisalloy 80 shims as a consequence of the dramatic friction force increments associated to wear abrasive mechanisms, and lower levels were found for shim materials characterized by adhesive wear mechanisms, such as aluminium, brass, bisalloy 400 and bisalloy 500.

<table>
<thead>
<tr>
<th>Material</th>
<th>Static Condition</th>
<th>Dynamic Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Friction Force (kN)</td>
<td>Friction Coefficient</td>
</tr>
<tr>
<td>Aluminium</td>
<td>69.5</td>
<td>0.34</td>
</tr>
<tr>
<td>Brass</td>
<td>65.0</td>
<td>0.37</td>
</tr>
<tr>
<td>Steel</td>
<td>49.3</td>
<td>0.48</td>
</tr>
<tr>
<td>Bisalloy 80</td>
<td>50.6</td>
<td>0.47</td>
</tr>
<tr>
<td>Bisalloy 400</td>
<td>60.9</td>
<td>0.390</td>
</tr>
<tr>
<td>Bisalloy 500</td>
<td>61.3</td>
<td>0.387</td>
</tr>
</tbody>
</table>

The static and friction coefficients per bolt were calculated using Equation 2 considering a proof load of 95kN and two shear planes. Values of the dynamic friction coefficients presented in Table 3 for brass, Grade 300 steel, bisalloy 80, and bisalloy 400 shims agree well with those reported by Clifton (2005) and Khoo et.al (2011). However, the value for aluminium was found to be less than the value reported by MacKinven (2006). Figure 9 presents the variation of the static and dynamic friction coefficients respect to the shim material hardness. It can be seen that the maximum friction coefficients were found for shim materials with medium hardness values ranging from 100BH to 300BH, in this case unstable hysteresis loops were recorded. In contrast, lower friction coefficient values and stable hysteresis loops were found for shim materials with either low hardness values ranging from 70BH to 100BH or high hardness values ranging from 300BH to 500BH.
5 CONCLUSIONS

This paper describes the hysteretic behaviour of Asymmetrical Friction Connections using different shim materials. It was shown that:

1. The torque control method can be considered as an objective and controllable methodology for assembling AFC specimens. Torque and nut rotation values for assembling AFC specimens using Belleville washers were suggested.

2. The hysteresis loop shape of Asymmetrical Friction Connections was found to be dependent on the sliding length of the connection. Ranges of sliding lengths where bilinear and almost square hysteresis loop shapes are expected were reported.

3. The stability of the hysteresis loop and the magnitude of the friction forces developed by AFC specimens were found to be directly related to the shim material hardness. Ranges of shim material hardness where stable hysteretic behaviours can be expected were reported.

6 REFERENCES


Figure 9. Variation of the friction coefficient according the shim material Brinell hardness value